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Effects of flameless catalytic infrared radiation on *Sitophilus oryzae* (L.) life stages[☆]

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ABSTRACT

A laboratory benchtop flameless catalytic infrared emitter was evaluated against all life stages of the rice weevil, *Sitophilus oryzae* (L.), an insect species associated with stored wheat. The emitted infrared radiation was in the 3–7 μm range. A non-contact infrared thermometer measured grain temperatures continuously during exposures of infested wheat. Insect mortality was a function of the final grain temperature attained. In general, higher grain temperatures were attained when using 113.5 versus 227.0 g of wheat, and at 8.0 cm from the emitter versus 12.7 cm, and during a 60 s exposure versus a 45 s exposure. Complete mortality of all life stages of *S. oryzae* was achieved at 8.0 cm from the emitter using 113.5 g of wheat, with a 60 s exposure; the mean grain temperatures attained ranged from 108.4 to 111.8 °C. The log odds ratio tests showed that eggs (0 days old) were the least susceptible stage to infrared radiation, followed by adults within kernels (28 days old), pupae (24 days old), young larvae (7 days old), larvae that were 14–21 days old, and adults (42 days old). These data using small amounts of grain indicate infrared radiation from the flameless catalytic emitter to be a viable option for disinfesting wheat containing various life stages of *S. oryzae*.

1. Introduction

Gas fired infrared radiation was evaluated three to four decades ago for its capacity to disinfest rice and other cereal grains (Tilton and Schroeder, 1961, 1963; Cogburn, 1967; Cogburn et al., 1971; Kirkpatrick and Tilton, 1972; Kirkpatrick et al., 1972; Tilton et al., 1972, 1983). The gas fired infrared radiation was generated with propane combusted on ceramic tiles producing more than 14.07 kW/h (48,000 BTU/h) of heat energy (Tilton and Schroeder, 1961; Kirkpatrick and Cagle, 1978). However, these gas fired infrared emitters had an open flame and produced temperatures in excess of 900 °C. Such high temperatures and open flames are not suitable for use in dusty grain storage and handling facilities due to explosion hazards. In previous evaluations of infrared radiation, different life stages of insects developing within kernels were not mentioned, and the grain temperatures were measured after infrared exposure and not in "real time", which resulted in underreporting actual temperatures attained by the grain.

Flameless catalytic infrared radiation is a new technology developed by Catalytic Drying Technologies LLC, Independence, KS, USA (www.catalyticdrying.com). It has been used primarily in the natural gas industry to heat pipes and in the automobile industry to dry paints, in addition to drying and disinfesting cereal grains (Pan et al., 2008). The flameless infrared radiation is emitted when propane or natural gas is combusted in the presence of a platinum catalyst resulting in temperatures of about 400 °C at the emitter surface. The only other co-products of this chemical reaction are water vapor and carbon dioxide (Gabel et al., 2006; Pan et al., 2008). Infrared radiation has been successfully used to inactivate enzymes and pathogenic bacteria, dehydrate food commodities, and disinfest durable commodities (Sandu, 1986; Gabel et al., 2006; Pan et al., 2008).

In the present investigation, the effectiveness of flameless catalytic infrared radiation was evaluated against different life stages of the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), an economically important internal pest of stored wheat (Sinha and Watters, 1985). Specific objectives were to examine the influence of grain quantity, distance from the infrared emitter, and exposure time on the susceptibility of *S. oryzae* eggs, larvae, pupae, and adults.

2. Materials and methods

2.1. Insect rearing

Cultures of *S. oryzae* were reared on 12% moisture content, organic, hard red winter wheat (var. Jagger), obtained from Heartland Mills, Marienthal, KS, USA, at 28 °C, 65% relative humidity (r.h.),

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and in a 14:10 (L:D) h lighting regime in a growth chamber (Model I-36 VL, Percival Scientific, Perry, IA) in the Department of Grain Science and Industry (GSI), Kansas State University (K-State), Manhattan, KS, USA.

2.2. Identifying *S. oryzae* life stages

In 24 ml vials, 5 g of 12% moisture content, organic wheat were infested with 20 unsexed adults of *S. oryzae*. There were five such vials. After 3 days, the adults were removed and the samples were incubated at 28 °C and 65% r.h. to obtain life stages of a specific age. Wheat samples infested for 3 days contained the egg stage (day 0), and infested samples incubated for 7, 14, 21, 24, and 28 days after day 0 represented various ages of *S. oryzae*. Each 5 g wheat sample in a vial was subjected to X-ray analysis (Model 43855A, Faxitron X-ray Corporation, Lincolnshire, IL, USA) to obtain images of insects at age 0, 7, 14, 21, 24, and 28 days. Kernels from these samples were spread in a monolayer on the sample holder and subjected to X-rays for 10 s at 28 kV. X-ray images were acquired using a digital camera. The digital images were used to score the ages of insects developing within wheat kernels. The digital images were given to six graduate students in the GSI department, who were not knowledgeable or who had no experience in scoring life stages of *S. oryzae* or any other internally developing stored-grain insect species. The students were asked to classify the ages of *S. oryzae* based on the digital images. An inaccurate classification resulted in a “0” score and an accurate classification resulted in a “1” score. These values were tallied to determine the accuracy, expressed as a percentage of the total number of students correctly classifying the stage/insect age. In addition, ages of each stage were determined by measuring the tunnel width within kernels made by developing immature stages. To measure the tunnel width, the top, middle, and bottom portions of the tunnel from each of the 48 infested kernels at a given insect age were measured and averaged. The exercise with naïve observers was necessary to determine the accuracy in classifying insect life stages or ages visually, rather than by making time-consuming tunnel width measurements with digital images.

2.3. Grain infestation and infrared treatment

The factors influencing the effectiveness of infrared against *S. oryzae* life stages included the grain quantity exposed (113.5 or 227.0 g), distance from the emitter (8.0 cm or 12.7 cm), and exposure time (45 or 60 s). Organic hard red winter wheat (113.5 or 227.0 g) of 12% moisture content was placed in 0.45 L glass mason jars fitted with filter paper and mesh lids, and each jar was infested with 100 unsexed *S. oryzae* adults of mixed ages. After 3 days, all introduced adults were separated from the wheat and the wheat was incubated at 28 °C and 65% r.h. for various time periods to obtain different *S. oryzae* ages for infrared exposure. The 3-days old jars represented the egg stage (day 0) of *S. oryzae*, while those held for 7, 14, 21, 24 and 28 days following day 0 represented various life stages or insect ages. The 28-days infested sample represented both adults that emerged and those that did not emerge from the kernels. Adults of *S. oryzae* were not separately added to wheat and exposed to infrared; however, wheat that was infested as explained above and held for 42 days from day 0 included the adults that were two weeks old.

A bench top catalytic infrared emitter, donated by Catalytic Drying Technologies LLC, was used for infrared exposure. The bench top model has a circular heating surface of 613.4 cm^2, and propane from a 473.0 ml container (Ozark Trail Propane Fuel, Bentonville, AR, USA) was the fuel used to start the initial reaction delivered at 28 cm of water column pressure. The total heat energy output of the unit was 1.47 kW/h (5000 BTU/h).

Wheat samples in a single-kernel layer were exposed to infrared radiation in a 3.8 cm deep steel pan of 27.9 cm diameter with a 43.0 cm long handle. Each infested grain quantity was exposed at 8.0 or 12.7 cm from the emitter surface for 45 or 60 s. Independent samples were exposed for each treatment combination, and each treatment combination was replicated three times. Wheat infested similarly, but unexposed to infrared radiation served as the control treatment, and the control treatments were replicated four times for each grain quantity and insect age.

The temperature of wheat in the pan during infrared exposure was measured continuously at the center of the steel pan using a non-contact infrared thermometer (Raynger MX4 Model 4TP78, Raytek®, Santa Cruz, CA, USA), placed far away from the emitter surface to prevent any interference. The infrared thermometer works in the 8–14 μm range. The non-contact thermometer was connected to a laptop computer via an RS-232 cable to record “real time” grain temperatures using a data acquisition program developed by the Electronic Design Laboratory at Kansas State University in LABView (National Instruments Corporation, Austin, TX, USA). The emissivity of the infrared thermometer was set to 0.95, and the temperatures recorded by the infrared thermometer were as accurate as those measured by a mercury thermometer, based on previous calibration experiments (Khamis, 2009; Khamis et al., 2010).

2.4. Assessment of insect mortality

Insect mortalities for 0, 7, 14, 21, 24, and 28 days samples in untreated wheat and wheat exposed to infrared were based on counting adults that emerged from kernels at 42 days from time 0. Since *S. oryzae* completes development within kernels, the effectiveness of infrared can be ascertained by examining the number of adults that emerged in infrared exposed wheat relative to emergence in untreated wheat. In 42 days old infested, untreated wheat samples *S. oryzae* adults had already emerged from kernels. Therefore, mortality of adults exposed to infrared radiation for this age group was determined directly by counting the number of living and dead adults. Adults were counted 24 h after exposure in untreated and infrared exposed wheat samples.

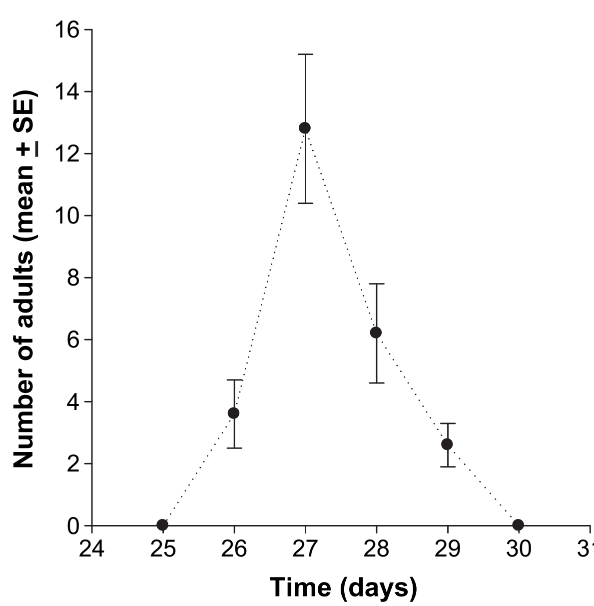

Fig. 1. Emergence (mean ± SE; $n = 5$) of *S. oryzae* adults from 5 g of wheat infested with 20 unsexed adults of mixed ages for 3 days. The adults were removed after 3 days and the samples incubated at 28 °C and 65% r.h. to determine the number of days required for the onset and cessation of adult emergence.

Table 1
Emergence of adults from infested wheat containing various ages of *S. oryzae*[a] not exposed to infrared radiation.

Insect age (days)	Mean ± SE ($n = 4$) number of adults in:	
	113.5 g	227.0 g
0 (eggs)	281.3 ± 22.0	403.3 ± 11.6
7	242.3 ± 39.2	403.3 ± 35.0
14	244.8 ± 29.6	380.0 ± 21.5
21	225.8 ± 12.8	398.3 ± 24.3
24	226.0 ± 9.9	395.0 ± 16.4
28	246.3 ± 44.4	447.3 ± 24.1
42 (adults)	216.8 ± 17.6	385.5 ± 18.6

[a] The ages correspond to when *S. oryzae* were exposed to infrared treatments.

2.5. Experimental design and data analysis

The experiment was run as a completely randomized design. The time-dependent temperature profile, averaged every second from replicated data, was plotted as a function of time for 113.5 and 227.0 g of wheat exposed for 45 and 60 s at 8.0 and 12.7 cm from the infrared emitter. There were eight temperature profiles for each insect age (total 56 temperature profiles). A comparison of temperature profiles across various ages showed that for any given quantity of grain, distance from emitter, and exposure time, the profiles were essentially similar, because all treatment combinations were conducted under the same controlled conditions.

The time-dependent temperature profile for each replicate was averaged over time to obtain a mean temperature attained by wheat during the exposure period. The mean wheat temperature attained for any given insect age, wheat quantity, and exposure time combination between 8.0 cm and 12.7 cm distance from the emitter surface was compared ($\alpha = 0.05$) using two-sample *t*-tests for equal variances (SAS Institute, 2002). Two-sample *t*-tests were used to compare differences in mean temperatures attained between a 45 and 60 s exposure at any given insect age, grain quantity and distance from emitter. Additionally, comparisons were also made of mean temperatures attained between 113.5 and 227.0 g of grain at any given insect age, distance from emitter, and exposure time.

In order to determine if the mean wheat temperature attained for a given quantity of grain, distance from emitter, and exposure time combination was consistent across the various ages tested (eggs [day 0], 7, 14, 21, 24, 28, and 42 days [adult emergence]) a linear regression of temperature versus insect age was performed and the slope was tested for deviation from zero at $\alpha = 0.05$ (SAS Institute, 2002). Non-significant differences indicated that the mean temperatures experienced by life stages were essentially similar.

The main effect of insect age, wheat quantity, distance from emitter, and exposure time and their two-way interactions on the probability of death were determined using logistic regression at $\alpha = 0.05$ (SAS Institute, 2002). Odds ratios from logistic regression were used to show differences in susceptibility (odds of dying) of various life stages exposed to infrared radiation. The odds ratio for adults (1) was used as a reference. A ratio >1 showed that a life stage was more susceptible than adults to infrared radiation while a ratio <1 showed that a stage was less susceptible than adults. Differences in susceptibility of various life stages was also determined by plotting probability of death as a function of mean wheat temperature averaged across wheat quantity, distance from emitter, and exposure time.

3. Results

3.1. Identifying S. oryzae life stages

Immatures of *S. oryzae* complete development inside the kernels, and therefore, the different life stages exposed to infrared radiation on specific days had to be confirmed using radiographic techniques. Eggs and different instars of *S. oryzae* were difficult to identify and distinguish in the kernel with the Faxitron, except at higher magnifications. Larvae in various phases of development were predominant between days 7 and 21, whereas pupae were predominant on day 24. In addition to pupae, a few old larvae were occasionally observed within kernels on day 24. A few *S. oryzae* adults were observed on day 28 within kernels; however by this time, most had already emerged as adults (Fig. 1). Adult emergence completely ceased after day 30.

Tunnel widths (mean ± SE) due to egg deposition (day 0) or developing larvae that are 7, 14, and 21 days old larvae were measured. Tunnel widths (mean ± SE) for 0, 7, 14, and 21 days insect ages were 0.26 ± 0.01, 0.57 ± 0.03, 0.72 ± 0.01, and 1.39 ± 0.01 mm, respectively. All six students were able to accurately classify (100% accuracy) the various insect ages from digital images alone.

3.2. Adult emergence in untreated samples

Consistently more *S. oryzae* adults emerged from 227.0 g of untreated, infested wheat compared with 113.5 g of wheat (Table 1). The mean number of adults that emerged from 113.5 g of wheat across the various insect ages ranged from 216.8 to 281.3, whereas from 227.0 g of wheat it ranged from 380.0 to 447.3.

3.3. Temperatures attained during infrared exposure

Higher temperatures were attained by 113.5 or 227.0 g of wheat exposed at a fixed distance from the emitter, but at a longer

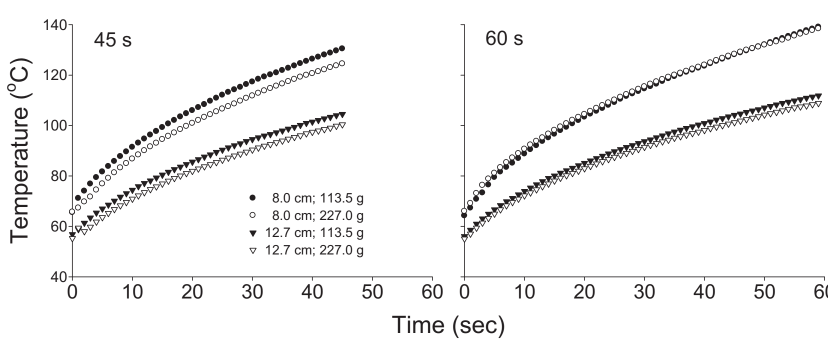

Fig. 2. A typical time-dependent temperature profile attained with 113.5 and 227.0 g of wheat exposed at 8.0 and 12.7 cm from the emitter for 45 or 60 s. During infrared exposures, temperature was measured continuously with an infrared thermometer connected to a computer. Each line represents mean temperature attained over time based on $n = 3$ measurements during infrared exposures.

exposure time. Temperature profiles for a given grain quantity, distance from emitter, and exposure time were similar, irrespective of insect age. Therefore, it was deemed necessary to show typical temperature profiles, out of 56, attained for the two grain quantities, two distances from the emitter, and the two exposure times (Fig. 2). The mean grain temperature attained was greatest (112.8 °C) in 113.5 g of wheat exposed for 60 s at a distance of 8.0 cm from the emitter (Table 2). The lowest mean temperature attained (79.2 °C) was in 227.0 g of wheat exposed for 45 s at a distance of 12.7 cm from the emitter.

Two sample *t*-tests for each life stage or *S. oryzae* age group (0, 7, 14, 21, 24, 28, and 42 days) showed that the mean temperature attained by 113.5 or 227.0 g of wheat during a 45 or 60 s exposure was significantly greater at 8.0 cm from the emitter when compared with mean temperature attained by wheat at 12.7 cm from the emitter (t, range among ages, grain quantities, and exposure times = 7.12–56.58; df = 4; $P < 0.0001$). The mean temperature attained by wheat after a 60 s exposure was significantly and consistently greater than those attained after a 45 s exposure at a given insect age, grain quantity, and distance from the emitter (t, range = −2.89 to −39.50; df = 4; $P \leq 0.0447$), except in four instances where mean temperatures attained after a 45 and 60 s exposure were similar (t, range = −1.19 to −2.39; df = 4; $P \geq 0.0749$).

Table 2
Emergence of *S. oryzae* adults from infested wheat in various infrared exposure treatments, mean temperature attained by wheat, and probability of insect death.

Insect age (days)	Grain quantity (g)	Distance from emitter (cm)	Exposure time (sec)	Mean temperature (°C)	Mean no. adults	Probability of death
0	113.5	8.0	45	103.2 ± 0.4	0	0.98
			60	108.4 ± 1.4	0	1.00
		12.7	45	81.1 ± 1.2	49.0 ± 2.6	0.89
			60	90.5 ± 0.8	0	0.99
	227.0	8.0	45	99.9 ± 0.1	139.3 ± 7.8	0.80
			60	107.5 ± 1.4	26.0 ± 3.2	0.92
		12.7	45	81.3 ± 0.4	295.7 ± 15.0	0.46
			60	87.6 ± 0.4	210.7 ± 3.9	0.69
7	113.5	8.0	45	100.9 ± 0.9	0	1.00
			60	109.9 ± 0.6	0	1.00
		12.7	45	82.7 ± 2.4	0	0.99
			60	86.1 ± 1.5	0	0.99
	227.0	8.0	45	102.1 ± 0.6	0	0.98
			60	109.1 ± 0.6	0	1.00
		12.7	45	81.3 ± 1.3	12.0 ± 4.3	0.98
			60	84.1 ± 0.5	0	0.95
14	113.5	8.0	45	106.2 ± 0.5	0	1.00
			60	112.3 ± 1.0	0	1.00
		12.7	45	84.9 ± 0.2	0	0.96
			60	88.6 ± 0.8	0	1.00
	227.0	8.0	45	102.3 ± 0.1	3.0 ± 2.1	0.98
			60	108.4 ± 0.2	0.3 ± 0.0	1.00
		12.7	45	81.8 ± 0.6	20.7 ± 5.5	0.68
			60	86.7 ± 1.1	3.0 ± 0.0	0.96
21	113.5	8.0	45	100.5 ± 0.8	0	1.00
			60	110.1 ± 0.8	0	1.00
		12.7	45	84.6 ± 0.1	0.7 ± 0.0	0.99
			60	92.4 ± 1.1	0	1.00
	227.0	8.0	45	101.4 ± 0.7	4.7 ± 2.7	0.98
			60	111.8 ± 0.6	0.3 ± 0.0	1.00
		12.7	45	81.7 ± 0.7	37.0 ± 7.0	0.92
			60	88.6 ± 0.5	6.0 ± 1.0	0.97
24	113.5	8.0	45	104.7 ± 1.5	0.3 ± 0.0	0.99
			60	110.1 ± 0.8	0	1.00
		12.7	45	82.8 ± 0.5	4.3 ± 0.7	0.97
			60	89.7 ± 0.5	1.3 ± 0.7	0.99
	227.0	8.0	45	102.5 ± 0.0	47.7 ± 22.8	0.95
			60	109.8 ± 0.6	8.0 ± 3.8	0.98
		12.7	45	82.9 ± 0.5	114.3 ± 23.3	0.97
			60	87.4 ± 0.5	55.0 ± 15.9	0.99
28	113.5	8.0	45	102.2 ± 0.7	0	0.99
			60	110.7 ± 0.9	0	1.00
		12.7	45	84.9 ± 0.5	16.8 ± 7.2	0.97
			60	90.8 ± 0.6	1.0 ± 0.6	0.99
	227.0	8.0	45	102.7 ± 0.8	21.2 ± 12.1	0.92
			60	110.4 ± 0.4	0.5 ± 0.0	0.97
		12.7	45	83.2 ± 0.3	114.8 ± 6.9	0.71
			60	87.9 ± 0.3	17.2 ± 7.7	0.79
42 (adults)	113.5	8.0	45	106.0 ± 0.8	0	1.00
			60	111.8 ± 1.1	1.0 ± 0.0	1.00
		12.7	45	86.1 ± 1.6	12.3 ± 1.5	1.00
			60	91.0 ± 0.7	0	1.00
	227.0	8.0	45	101.0 ± 1.5	10.7 ± 5.8	1.00
			60	111.8 ± 1.1	1.0 ± 0.0	1.00
		12.7	45	82.1 ± 1.3	60.0 ± 12.3	0.94
			60	88.7 ± 0.6	48.0 ± 3.6	0.98

In general, grain quantity had the least influence on the mean grain temperatures attained for any given insect age, distance from emitter, and exposure time. In 20 out of the 28 comparisons, the difference in mean temperature attained by 113.5 and 227.0 g of wheat was not significant (t, range $= -2.75$–2.51; df $= 4$; $P \geq 0.5130$). In eight other cases, mean temperatures attained by wheat were significantly higher in 113.5 than in 227.0 g of wheat (t, range $= -4.29$–8.10; df $= 4$; $P \leq 0.0018$).

The slope of the linear regression between the mean temperatures attained by 113.5 or 227.0 g of wheat at 8.0 or 12.7 cm from the emitter after a 45 or 60 s exposure and insect age was not significantly different from zero (t, range among grain quantities, distance from emitter, and exposure times $= -1.86$–1.54; $n = 7$; $P \geq 0.1222$).

Adults of *S. oryzae* were not observed in 20 out of the 56 infrared treatment combinations (Table 2), indicating complete mortality. In the remaining 36 infrared treatment combinations, the mean number of adults that emerged ranged from 0.3 to 295.7. Insect mortality in most cases was directly related to the mean grain temperatures attained. Complete mortality of all insect ages was achieved in 113.5 g of grain, exposed for 60 s, at 8.0 cm from the emitter surface. Exposure of all insect ages in 227.0 g of wheat for 45 s at a distance 12.7 cm from the emitter resulted in 46–99% mortality.

Logistic regression indicated that insect age ($\chi^2 = 1438.81$; df $= 6$ $P < 0.0001$), wheat quantity ($\chi^2 = 5.881$; df $= 1$ $P < 0.0153$), distance from emitter ($\chi^2 = 114.68$; df $= 1$ $P < 0.0001$), and exposure time ($\chi^2 = 5.055$; df $= 1$ $P < 0.0246$) influenced the probability of death of *S. oryzae*. All two-way interactions (insect age $\times$ wheat quantity, insect age $\times$ distance from emitter, insect age $\times$ exposure time [df $= 6$]; wheat quantity $\times$ distance from emitter, wheat quantity $\times$ exposure time, and distance from emitter $\times$ exposure time were highly significant (χ^2 range $= 7.80$–211.61; P, range $= <$ 0.0001–0.0052).

The probabilities of death plotted as a function of mean grain temperature showed variation among stages (Fig. 3). Increasing the temperatures resulted in higher probabilities of death, irrespective of insect age, and these probabilities were close to 1 (100% mortality). Generally, a mean temperature of about 110 °C for 60 s was needed to achieve 100% mortality, irrespective of insect age. The eggs of *S. oryzae* were the least susceptible stage (odds ratio, 0.02), followed by adults within kernels (28 days old; 0.14), pupae (24 days old, 0.18), young-to-old larvae (7–21 days old; range, 0.49–0.73), and 42-days-old adults (1).

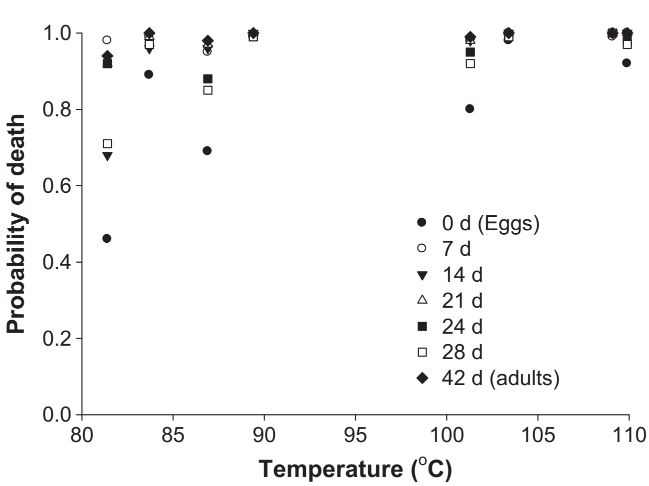

Fig. 3. Probability of death of different life stages of *S. oryzae* as a function of mean wheat temperature. The probability of death was averaged across different grain quantities, distances from the emitter, and exposure times.

4. Discussion

Females of *S. oryzae*, after mating, chew a shallow hole in the kernel to lay a single egg. After egg laying, the hole is sealed with a gelatinous plug (Kirkpatrick and Wilbur, 1965; Sharifi and Mills, 1971). Larvae hatch from eggs and complete development within kernels (Arbogast, 1991; Pearson et al., 2003). Larval instars of *S. oryzae* within wheat kernels can be identified by head capsule width or by tunnel widths produced by developing larvae (Sharifi and Mills, 1971). Sharifi and Mills (1971) reported both head capsule widths and tunnel widths for the four *S. oryzae* instars. The mean tunnel widths, indicative of each instar, reported by Sharifi and Mills (1971) were 0.31 (range, 0.30–0.37), 0.51 (0.43–0.62), 0.83 (0.70–0.97), and 1.34 (1.20–1.48) mm, respectively. The measured mean tunnel width on day 0 in our study was 0.26. At this time only eggs were present and not first instars, which is in agreement with the observations of Sharifi and Mills (1971) who reported the diameter of the egg cavity to be 0.25–0.30 mm. The tunnel widths for 7, 14, and 21 days old larvae in our study were within ranges reported by Sharifi and Mills (1971) for second through fourth instars.

The consistently greater adult progeny production in 227.0 g of wheat compared with 113.5 g could be due to the availability of more suitable kernels for egg laying or due to the presence of kernels that weighed ≥20 mg. Campbell (2002) reported *S. oryzae* to lay more eggs in kernels that were ≥20 mg. These differences could also arise from natural variability in the number of eggs laid by the mixed age adults used in our study. For example, Soderstrom (1960) infested 150 g of wheat grain with 150 unsexed *S. oryzae* adults for 3 days, the same time period used in this study. The mean number of adults that emerged ranged from 162 to 258. Cogburn (1967) infested 2200 g of rice (infestation density of 1 insect/g) with *S. oryzae* for 7 days. This quantity of rice was then divided into 50 g lots. The number of adults that emerged from untreated 50 g wheat lots ranged from 144 to 285. The fact that large number of adults emerged from infested untreated wheat samples indicated that our experimental protocol was robust, and can be used to gauge the effectiveness of infrared radiation by comparing adult emergence from infrared-exposed versus untreated wheat samples.

Radiographic analysis is one of many methods used to determine internal infestation (Dennis and Decker, 1962; Haff and Pearson, 2004). The age or stage of internally developing insects, including *S. oryzae*, was unknown in previous research with infrared treatments of grain. Therefore, we used radiographic analysis to determine the insect stage subjected to infrared treatments. The accurate scoring by students also indicated that the digital images alone were sufficient to quickly age-grade *S. oryzae* by visual inspection.

Exposure time and distance from the emitter had a greater influence on the mean temperatures attained than grain quantity. Generally, mortality of insect stages was directly related to the mean temperatures attained. However, there were instances where the same mean temperature attained did not result in the same mean probability of death for a given insect age. For example, in Table 2 the mean temperature attained by 113.5 and 227.0 g of wheat exposed for 45 s at 12.7 cm from the emitter was essentially similar (81 °C). However, the probability of death was 0.89 in 113.5 g of wheat and 0.46 in 227.0 g of wheat. In other cases, the probability of death for a given insect age was the same, but the mean temperatures attained were different.

The plot of probability of death as a function of insect age also showed variability in how different ages responded to the same mean wheat temperature, especially below 100 °C. These findings suggest that mean temperature alone may not be a good predictor of insect death. An understanding of the amount of infrared radiation that is reflected, scattered, and absorbed at the two grain quantities, exposure times, and distances may shed some light on the insect responses observed.

We found eggs to be the most tolerant stage to infrared radiation. Kirkpatrick (1975) reported only 8% mortality of eggs and first instars exposed to infrared radiation. Flameless catalytic infrared radiation is a viable tool for disinfesting organic and non-organic stored wheat, and our study showed that temperatures of 90–112 °C for 60 s were necessary to produce 99–100% mortality of all life stages of *S. oryzae*. At the treatment combinations reported in this paper, there were no adverse physical, chemical, rheological, and end-use quality effects on infrared exposed hard red winter wheat (Khamis, 2009). Future work should focus on developing customized on-line systems capable of rapid disinfestation of wheat at farm bin sites, grain elevators, and grain-processing facilities.

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